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FRAGILITY CURVES FOR LOW-RISE, MID-RISE AND HIGH-RISE CONCRETE MOMENT RESISTING FRAME BUILDING FOR SEISMIC VULNERABILITY ASSESSMENT

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ABSTRACT

The aim of the study is to develop the fragility curves for low-rise, mid-rise, and high-rise concrete moment resisting framebuildings. The concrete moment resisting frame buildings were designed as per Indian seismic design code. The slab elements were modelled as membrane type, shell type and their influence on the probability of damage states obtained from fragility curves is also studied. For the development of the fragility curves, guidelines provided by HAZUS-MH MR4 technical manual has been used. For the analysis, concrete moment resisting frames weremodeled using ETABS. The nonlinear behavior has been incorporated using default plastic hinges in accordance with ASCE 41-13. Spectral demand and spectral capacity curves obtained from the nonlinear static pushover analysis are used for plotting fragility curves. Fragility curves were developed keeping spectral displacement as ground motion parameters.

Key words: Seismic Vulnerability, Pushover Analysis, Fragility Curves, Damage states.

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1. INTRODUCTION

In past decades, earthquakes have proven to cause several costly and destructive consequences and this is going to recur again. An effort to predict and reduce the risks and consequences due to this natural calamity is the only thing that can be done. The earthquakes and fragility of the structures caused due to these natural calamities cause high risk. These

risk components have inherent uncertainties including structural and seismic uncertainties. In an effort to employ these uncertainties, it is required toassess seismic performance and vulnerability of buildings for a given seismic parameter. The seismic vulnerability of structures is generally expressed through probabilistic fragility functions representing the conditional probability of reaching or exceeding a pre-defined damage state given the measure of earthquake ground shaking. In this current study Capacity Spectrum method, an analytical approach has been adopted to assess the seismic vulnerability[1].

Nonlinear static pushover analysis has been carried out for development of fragility curves. In this analysis, the structure is subjected to monotonically increasing lateral loads till the target displacement has been reached.. From this analysis base shear vs.roof displacement curve is obtained, which are further converted to acceleration displacement response spectrum format as per the criteria given in FEMA 440[2].Krawinkler and Seneviratna [3] studied that the nonlinear behaviours such as yielding and failure mechanism are obtained using nonlinear staticpushover analysis.

For the generation of the fragility curve, HAZUS MH-MR4 technical manual [4] has been used. Concrete moment resisting frame structures with different number of stories:1-3 stories (low rise building), 4-7 (mid rise building) and 8-12 (high rise building)as defined in HAZUS-MH MR4 has been considered. Each of these structures was modeled and analyzed as Frame with the membrane as slab type, Frame with the shell as slab type. Pushover analysis was carried out using ETABS[5]. Results from the pushover analysis were used for plotting the fragility curves and to evaluate the probability of damage the stucture sustains due to seismic ground vibration.

Kircil and Polat(2006) [6]have presented a study on developing the fragility curves for mid-rise reinforced concrete frame buildings located in Istanbul. They performed incremental dynamic analysis on 3, 5 and 7 story buildings using twelve artificial ground motions.Based on the obtained capacities, fragility curves were obtained keeping elastic pseudo spectral acceleration, peak ground acceleration(PGA) and elastic spectral displacement as ground motion parameters.Saruddinand Nazri(2015) [7] have presented a study on fragility curve for low- and mid-rise buildings located in Malaysia that are reinforced concrete and steel moment-resisting frames.The two models which included three and six story frame structures with different types of material were analysed using Incremental Dynamic Analysis which was conducted under seven sets of ground motion records using SAP2000 software and scaling peak ground acceleration was increased for every 0.05 g until it achieved 0.6 g.Vasavada (2016) [8] have presented a study on development of fragility curves for R/C building using HAZUS method. A typical 10 storeyed 6 bay R/C frame building was modelled in SAP 2000 for performing non-linear static analysis. The two building frame models were considered one without considering infill wall stiffness and another with considering stiffness of the infill wall.

2. DESCRIPTION OF MODELS

All the models considered in the study are 3D frame structures having three bays both in X and Y directions. The width of the each bay is 4.5m and 3.5m in X and Y directions respectively. The height of each storey is 3m. The models were assumed fixed to the base. The different structural model types considered for the study are labelled as shown in Table I.

Table 1 Labelling of models

	Building type	Low-rise building			Mid-rise building				High-rise building				
	Number of storey	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Frame with the membrane as slab type		FM 1	FM 2	FM 3	FM 4	FM 5	FM 6	FM 7	FM 8	FM 9	FM 10	FM 11	FM 12
Frame with the shell as slab type		FS 1	FS 2	FS 3	FS 4	FS 5	FS 6	FS 7	FS 8	FS 9	FS 10	FS 11	FS 12

Each structure has been designed in accordance with IS: 456-2000 [9] for different load combinations specified in Indian Standards. The slab is 150 mm thick with concrete of grade M30. The beams are of dimensions 300mm X 600mm with a grade of concrete M25. Columns along the periphery of the plan have dimensions 300mm X 500mm and in the interior of the plan as shown in Fig.1have dimensions 300mm x 600mm, with both the column types having concrete of grade M30. Unit weight of concrete is assumed to be 25 kN/m^3. The structures were assumed located in Zone V having soil type II according to IS: 1893 (part-1)-2002 [10].A floor finish of 1kN/m^2 has been assumed along with a live load of 3 kN/m^2 for all floor levels, except for roof level the live load assumed is 1.5 kN/m^2. High Yielding Strength Deformed bars of grade 415 are used for reinforcing the concrete.

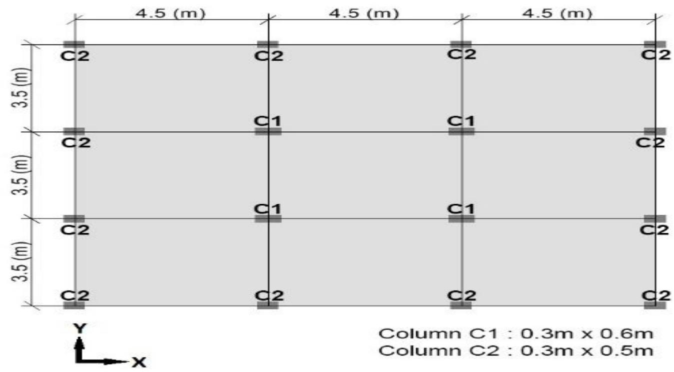

Figure 1 Plan

3. NONLINEAR SIMULATION

Default hinges in accordance with ASCE 41-13 [11] have been assigned to the structural elements in order to carry out the nonlinear behaviour. For beam elements, plastic hinges governed by the major axis bending have been assigned at its two ends whereas for columns, plastic hinges governed by the interaction of the axial force and biaxial bending moments is assigned at both of its ends.

4. PUSHOVER ANALYSIS OF FRAME STRUCTURE

An initial linear analysis of the model is done under gravity load to determine the forces in the columns and beams. The cross section properties are determined based on this analysis. Default hinges in accordance with ASCE 41-13are assigned.The structure is subjected to a load pattern consistent with IS 1893 (part-1):2002 in both longitudinal ‘X’ and transverse ‘Y’directions.

In this study, seismic demands spectral displacement and spectral acceleration are used for generation of the fragility curves. The target displacement is fixed at 4% of the height of the structure as per ATC-40[12] guidelines. P-δ effect has been incorporated considering the geometric non-linearity parameter. Displacement controlled pushover analysis is carried out after the gravity loads have been applied with the help of commercially available software: ETABS.

For seismic vulnerability assessment, the pushover curves in X and Y directions are converted into ADRS (Acceleration Displacement Response Spectrum) format in accordance with FEMA 440. The obtained capacity curves are bi-linearized to obtain yield spectral displacement (S_{dy}) and ultimate spectral displacement values (S_{du}). The values of the yield and ultimate spectra displacement are used to obtain values of medians at different damage states.

The values of medians at different damage states are obtained from damage state model proposed by Lantada*et al.*[13].

Table 2 Damage State Thresholds

Damage states	Median value of Spectral Displacement, : $\overline{S_{d,ds}}$
Slight	$0.7\ S_{dy}$
Moderate	S_{dy}
Extensive	$S_{dy}+0.25(S_{du}- S_{dy})$
Complete	S_{du}

5. DEVELOPMENT OF FRAGILITY CURVES

Damage states define the physical condition of the building subjected to strong earthquake ground motion. Damage states for Concrete Moment Resisting Frame building type are described in HAZUS-MH MR4 technical manual. They are slight, moderate, extensive and complete.

Building fragility curves are lognormal functions which describe the probability of reaching or exceeding, structural and nonstructural damage states, given median estimates of the spectral response for example spectral displacement. In this study, spectral displacement is used to express the severity of ground motion. Fragility curves are plotted for both longitudinal 'X' direction and transverse 'Y' direction for different building models.

The probability of being in or exceeding a given damage state is modeled as a cumulative lognormal distribution. For structural damage states,given the spectral displacement, S_d, the probability of being in or exceeding a damage state, ds, is modeled as

$$P[ds|S_d]=\Phi\left[\frac{1}{\beta_{ds}}\ \ln\left(\frac{S_d}{\overline{S_{d,ds}}}\right)\right] \qquad (1)$$

Where: $\overline{S_{d,ds}}$is the median value of spectral displacement at which the building reaches the threshold of damage state, ds,

$\beta_{ds}$is the standard deviation of the natural logarithm of spectral displacement for damage state, ds,

Φ is the standard normal cumulative distribution function.

P $[S|S_d]$,P $[M|S_d]$, P $[E|S_d]$, P $[C|S_d]$ indicate probability of being in or exceeding slight (S), Moderate (M), Extensive (E) and Complete(C) respectively.

Sets of Damage State Betas" β_{ds}" for each of the three building height groups is selected from the"Building Fragility Betas"table given in HAZUS-MH MR5technical manual [14] for appropriate values of degradation or Kappa factors, damage variability and capacity curve

variability. In this study, damage state variability values are chosen considering moderate cases of degradation and moderate curve variability.

Table 3 Damage state beta values

Damage state (ds)	Damage State Beta " β_{ds}"		
	Low rise building	**Mid rise building**	**High rise building**
Slight	0.8	0.75	0.7
Moderate	0.95	0.85	0.8
Extensive	1.05	1	1
Complete	1.05	1	1

6. RESULTS AND DISCUSSIONS

The results obtained after carrying out non-linear static analysis are compared and discussed. Fig.2 and Fig.3 show pushover curves for 2 storey Concrete Moment Frame. It can be inferred from following pushover curves that the lateral stiffness of frame with the shell as slab type:FS2 is more when compared to other building type:FM2.The structural model type FM2 has lesser performance in resisting base shear when compared to the structural model type FS2.This can be due shell element taking part in load bearing along with transferring loads to beams.

The lateral stiffness offered by the structural model types is high for pushover analysis in X direction when compared to that in Y direction. This is due to structural models having higher moment of inertia along the Y direction. Also the ductile behaviour exhibited for push in X direction is good when compared to push in Y direction.

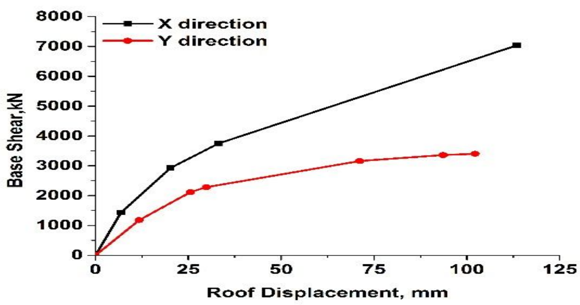

Figure 2 Pushover Curves for structural Model type FS2 obtained from pushover analysis in X and Y direction

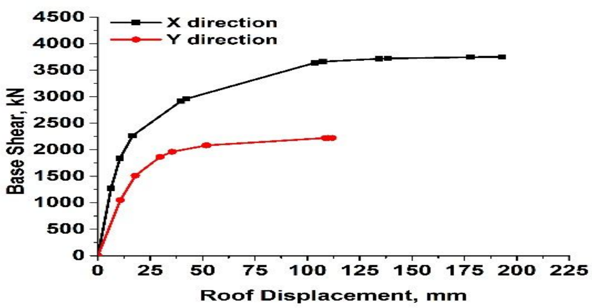

Figure 3 Pushover Curves for structural Model type FM2 for obtained from pushover analysis in X and Y direction

Fig.4, and 5 shows the performance point obtained by the intersection of the capacity spectrum and demand spectrum for structural model types FS2, FM2 respectively. The spectral displacement and spectral acceleration at performance point for structural model type FS2, FM2 in X direction are (10mm, 0.8423g), (8.5mm, 0.7447g) and in Y direction are (19.7mm, 0.8030g), (19.4mm, 0.6799g) respectively. The spectral displacement at performance point in X direction is less when to that in Y direction, which suggests that structure displaces less in X direction when compared to that in Y direction. Also, spectral acceleration at performance point in X direction is more when to that in Y direction, which suggests that structure accelerates more in X direction when compared to that in Y direction. Fig.6is representation of capacity curves in its bilinear form.($S_{dy, x}$, $S_{ay, x}$),($S_{dy, y}$,$S_{ay, y}$) defines Spectral yield point in X and Y directions.($S_{du, x}$, $S_{au, x}$)), ($S_{du, y}$, $S_{au, y}$)defines Spectral ultimate capacity points in X and Y directions respectively.

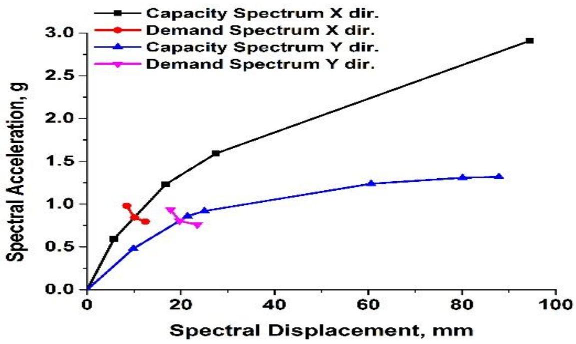

Figure 4 Capacity Spectrum vs. Demand spectrum for structural model type FS2

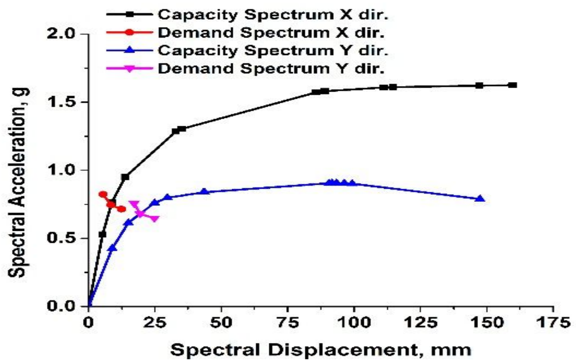

Figure 5 Capacity Spectrum vs. Demand spectrum for structural model type FM2

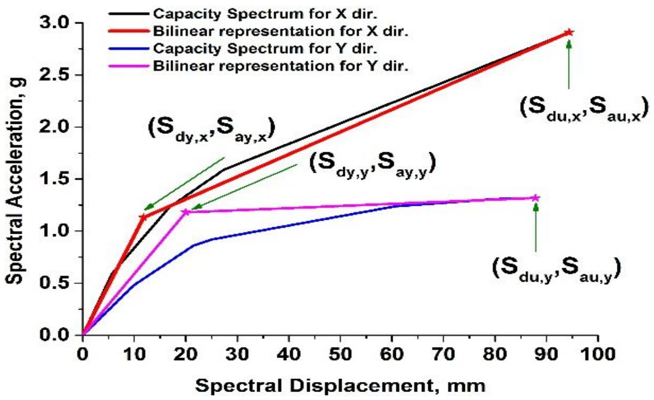

Figure 6 Conversion of Capacity curves into Bilinear form for the structural model FS2

Fig.7 and 8 show fragility curves plotted for structural model types FS2in X and Y directions respectively. A vertical line is drawn in both plots at the spectral displacement 10mm and 20mm which corresponds to the performance point obtained from pushover analysis in X and Y directions respectively. The slight and moderate damage states are dependent on Spectral yielding of the structure. At performance point, the discrete probability of slight and moderate damage state being reached by structural model type FS2 is more in X direction when compared to that in Y direction. This can be due to early yielding at lower displacement for push in X direction which is evident from Fig.2. But the discrete probability of extensive and complete damage state reached by the same model type FS2 is more in Y direction when compared to that in X direction which can be due to reduced lateral stiffness and lesser ductile performance in post yielding phase of the structure. The probability of structural model FS2 not reaching any of the structural damage state is more in X direction when compared to that in Y direction, which can be accounted for building having greater lateral stiffness in X direction due to the higher moment of inertia of whole building along Y direction.

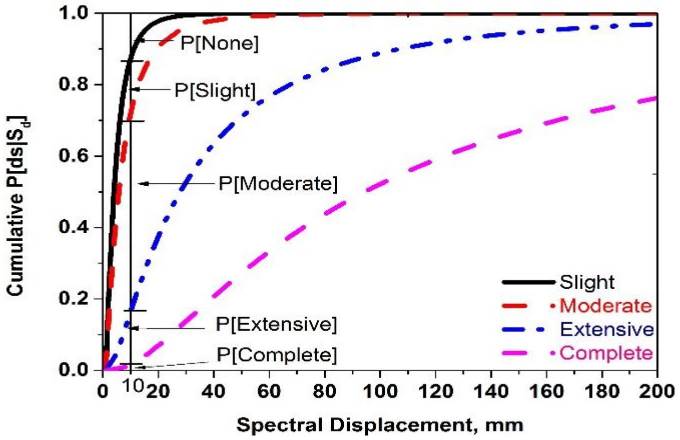

Figure 7 Fragility Curves for structural model type FS2obtained from pushover analysis in X directionin

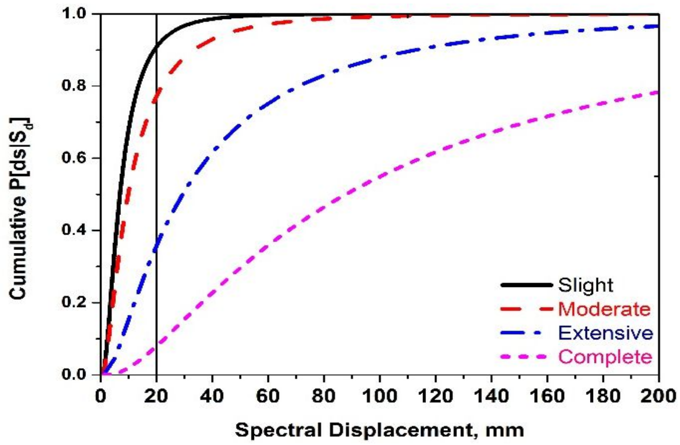

Figure 8 Fragility Curves for structural model type FS2 obtained from pushover analysis Y direction

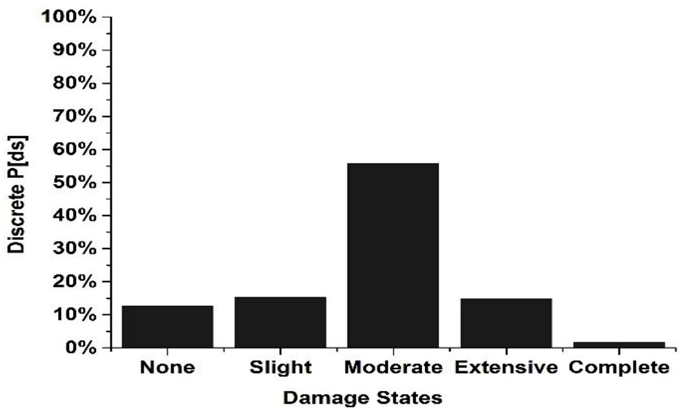

Figure 9 Discrete Probability of damage for structural model type FS2 in X direction at the performance point

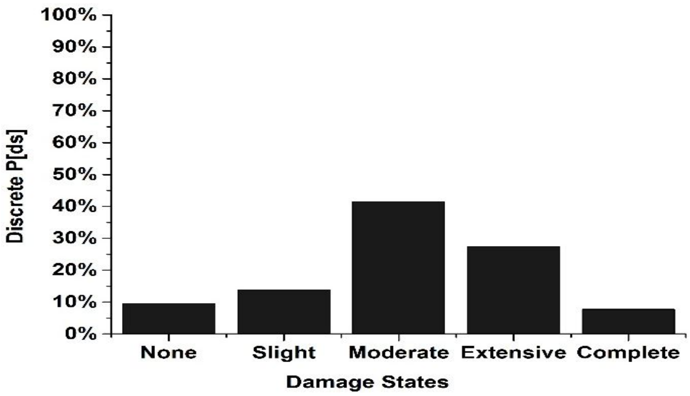

Figure 10 Discrete Probability of damage for structural model type FS2 in Y direction at the performance point

Table IV, V shows the Discrete probability of different damage states being reached by different structural model types at performance point for the nonlinear static analysis in X and Y directions. Due to larger stiffness, the performance point for one storey structural model types could not obtained. From table IV& V, it is evident that discrete probability of none and slight damage states the structural models except FS2, FM2 reach at performance point is high for pushover in Y direction when compared to that in X direction.

The probability of the moderate damage state the structural model types reach is high for pushover in X direction when compared to that in Y direction. This might be due to structural model getting accelerated more in X direction due to higher global moment of inertia of structure along Y direction. Hence the structure starts to yield at lower spectral displacement for push in X direction when compared to push in Y direction.

The complete damage state probability is high for pushover in Y direction when compared to that in X direction. This is might be due to structural models exhibiting poor ductile performance in Y directions than in X direction before collapse.

For the pushover in X direction, the entire structural model reaching the moderate damage state is high when compared to other damage states. For the pushover in Y direction, the structural models FM2-FM12 reaching the moderate damage state is high when compared to other damage state. But for structural model types FS3-FS12 reaching the extensive damage state is high when compared to other damage states. For structural model type FS2 moderate damage predominates.

The maximum probability of damage at the performance point for frame with the shell as slab type is 63.26% and 41.48% for push in X and Y directions respectively and lies in the

moderate damage state. Therefore the structural model type FS4, FS2 are vulnerable for pushover analysis in X and Y directions respectively.

Table 4 Discrete Probability of damage for Frame with the shell as slab type at the performance point

Structural Model type	Discrete Probability of damage, (%)									
	Damage States									
	None		Slight		Moderate		Extensive		Complete	
	X dir.	Y dir.	X dir.	Y dir.	X dir.	Y dir.	X dir.	Y dir.	X dir.	Y dir.
FS2	12.62	9.5	15.20	13.83	55.75	41.48	14.8	27.47	1.63	7.72
FS3	2.81	3.63	8.08	9.16	62.98	27.04	22.84	35.20	3.29	24.98
FS4	0.33	2.33	2.05	6.75	63.26	28.42	29.82	37.20	4.54	25.30
FS5	0.24	2.10	1.67	6.37	42.36	28.07	40.42	37.46	15.32	26.00
FS6	0.22	2.85	1.58	7.54	59.98	29.20	32.61	36.67	5.62	23.74
FS7	0.23	2.73	1.63	7.37	47.82	28.19	39.59	36.58	10.74	25.13
FS8	0.13	1.98	1.28	6.80	50.48	30.80	38.47	36.86	9.65	23.55
FS9	0.14	1.15	1.38	5.00	47.82	26.67	39.63	37.19	11.03	29.98
FS10	0.15	1.01	1.45	4.63	49.34	25.36	38.83	36.91	10.23	32.09
FS11	0.16	1.09	1.49	4.84	43.85	25.08	41.10	36.53	13.40	32.46
FS12	0.17	1.21	1.56	5.14	42.47	24.45	41.48	35.85	14.32	33.36

The maximum probability of damage at the performance point for frame with the membrane as slab type lies in moderate damage state with discrete probability being 63.31% and 45.55% for push in X and Y directions respectively. Hence the structural model type FM2 is vulnerable.

Table 5 Discrete Probability of damage for Frame with the membrane as slab type at the performance point

Structural Model type	Discrete Probability of damage, (%)									
	Damage States									
	None		Slight		Moderate		Extensive		Complete	
	X dir.	Y dir.	X dir.	Y dir.	X dir.	Y dir.	X dir.	Y dir.	X dir.	Y dir.
FM2	14.89	7.86	15.92	12.87	63.31	45.55	5.62	27.06	0.26	6.67
FM3	2.56	4.58	7.71	10.22	56.18	43.39	28.03	31.89	5.51	9.93
FM4	1.50	3.64	5.24	8.59	58.66	45.35	29.45	33.01	5.16	9.42
FM5	1.14	3.52	4.46	8.45	57.15	43.38	31.32	33.99	5.93	10.66
FM6	1.45	2.72	5.15	7.34	56.36	40.15	31.04	36.26	6.00	13.54
FM7	0.94	2.89	3.97	7.59	49.84	39.26	36.03	36.23	9.22	14.04
FM8	0.99	2.32	4.56	7.42	51.87	40.49	34.24	35.87	8.34	13.89
FM9	0.65	2.36	3.55	7.48	50.67	39.16	35.89	36.12	9.23	14.89
FM10	0.65	2.50	3.56	7.71	52.18	38.39	35.11	36.03	8.50	15.37
FM11	0.63	2.56	3.48	7.81	50.05	37.45	36.20	36.09	9.64	16.10
FM12	0.87	2.70	4.24	8.04	48.61	36.81	36.17	35.95	10.11	16.50

7. CONCLUSION

In this study, fragility curves are plotted for concrete moment resisting frame buildings and following conclusion can be stated

- For frame with membrane as slab type, the probability of moderate damage state at performance point is high when compared to other damage state. This damage state probability is high for pushover analysis in X direction when compared to that in Y direction. Results show that the structural model type FM2 is vulnerable.
- For frame with shell as slab type, when compared to other damage states the probability of moderate damage at performance point is high for pushover analysis in X direction. The extensive probability predominates for push over analysis in Y direction except for structural

model type FS2. Also, the structural model type FS4, FS2 are vulnerable for pushover analysis in X and Y directions respectively.

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